

# Light Neutralinos and WIMP direct searches\*

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The predictions of our previous analysis about possible low-mass ( $m_\chi \lesssim 50$  GeV) relic neutralinos are discussed in the light of some recent results from WIMP direct detection experiments. It is proved that these light neutralinos are quite compatible with the new annual-modulation data of the DAMA Collaboration; our theoretical predictions are also compared with the upper bounds of the CDMS and EDELWEISS Collaborations.

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Searches for neutralinos at colliders have not yet reached the sensitivity required to place a direct lower bound on the neutralino mass  $m_\chi$ . The commonly quoted and employed bound  $m_\chi \gtrsim 50$  GeV is derived from the lower bound on the chargino mass determined at LEP2 ( $m_\chi^\pm \gtrsim 100$  GeV) under the assumption that the  $U(1)$  and  $SU(2)$  gaugino masses  $M_1$  and  $M_2$  satisfy the standard relationship  $M_1 \simeq \frac{1}{2}M_2$  at the electroweak scale. This hypothesis is a consequence of the assumption that these mass parameters have a common value at the grand unification (GUT) scale.

In supersymmetric models with R-parity conservation and no gaugino-unification assumption at the GUT scale, an absolute lower limit on  $m_\chi$  cannot be derived from the lower bound on the chargino mass. Instead, it may be established by applying the upper bound on the Cold Dark Matter (CDM) content in the Universe,  $\Omega_{CDM} \equiv \rho_{CDM}/\rho_c$ , in combination with constraints imposed on the Higgs and supersymmetric parameters by measurements at colliders and other precision experiments (muon  $g-2$ ,  $BR(b \rightarrow s + \gamma)$ ). This point was discussed in Refs. [1, 2], where a lower bound on the neutralino mass of about 6 GeV was established as a consequence of the recent  $2\sigma$  C.L. upper-limit  $\Omega_{CDM}h^2 \leq 0.131$  obtained by the analysis of the WMAP data [3].

In Refs. [1, 2] we also analyzed the properties of light ( $m_\chi \lesssim 50$  GeV) relic neutralinos from the point of view of their detection rates in WIMP direct search experiments. Two main properties were pointed out: 1) direct detection rates for neutralinos of mass lighter than

50 GeV reach levels within sensitivities of current WIMP direct-detection experiments; 2) in the mass range  $6 \text{ GeV} \lesssim m_\chi \lesssim 25 \text{ GeV}$  the detection rates are predicted to fall in a very restricted range (this is at variance with what happens at higher  $m_\chi$ , where the detection rates in an effective supersymmetric MSSM scheme (effMSSM) vary over decades [4]). As shown in Refs. [1, 2] the property (2) is a consequence the fact that the detection rate has a lower bound induced by the upper limit on  $\Omega_{CDM}h^2$ .

Recalling that, for neutralino-matter interactions, coherent effects systematically dominate over spin-dependent ones, the aforementioned properties (1)–(2) are conveniently displayed in terms of the quantity  $\xi\sigma_{\text{scalar}}^{(\text{nucleon})}$ , where  $\sigma_{\text{scalar}}^{(\text{nucleon})}$  is the neutralino-nucleon scalar cross-section and  $\xi$  is a rescaling factor between the neutralino local matter density  $\rho_\chi$  and the total local dark matter density  $\rho_0$ :  $\xi \equiv \rho_\chi/\rho_0$ . Following a standard assumption,  $\xi$  may be taken as  $\xi = \min(1, \Omega_\chi h^2/(\Omega_{CDM}h^2)_{\min})$ .

The supersymmetric model considered in the present paper is an effMSSM scheme at the electroweak scale, with the following independent parameters:  $M_2, \mu, \tan\beta, m_A, m_{\tilde{q}}, m_{\tilde{l}}, A$  and  $R \equiv M_1/M_2$ . Notations are as follows:  $\tan\beta$  the ratio of the two Higgs v.e.v.'s:  $\tan\beta \equiv \langle H_2^0 \rangle / \langle H_1^0 \rangle$ ,  $\mu$  is the Higgs mixing mass parameter,  $m_A$  the mass of the CP-odd neutral Higgs boson,  $m_{\tilde{q}}$  is a soft-mass common to all squarks,  $m_{\tilde{l}}$  is a soft-mass common to all sleptons,  $A$  is a common dimensionless trilinear parameter for the third family,  $A_{\tilde{b}} = A_{\tilde{t}} \equiv Am_{\tilde{q}}$  and  $A_{\tilde{\tau}} \equiv Am_{\tilde{l}}$  (the trilinear parameters for the other families being set equal to zero). Since we are here interested in light neutralinos, we consider values of  $R$  lower than its standard value:  $R_{\text{GUT}} \simeq 0.5$ ; for definiteness, we take  $R$  in the range: 0.01 - 0.5. In the scanning of the supersymmetric parameter space,

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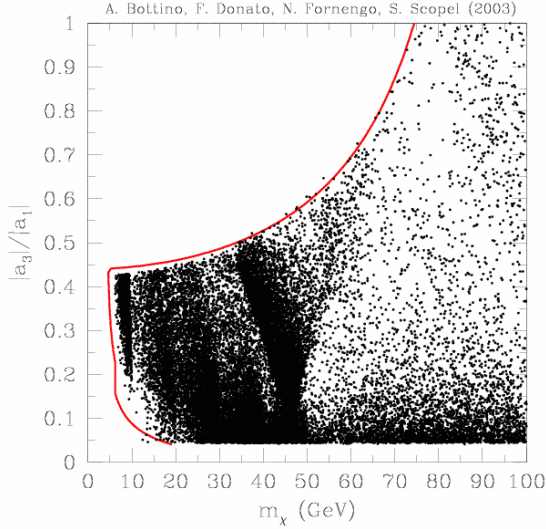


FIG. 1: Ratio of the  $\tilde{H}_1^0$  content to the  $\tilde{B}$  content in the neutralino composition as a function of the neutralino mass  $m_\chi$ . The upper branch of the solid line derives from neutralino diagonalization (see text), while the lower one is obtained from  $\Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{\max} = 0.131$ .

we use the following ranges of the MSSM parameters:  $1 \leq \tan \beta \leq 50$ ,  $100 \text{ GeV} \leq |\mu|, M_2, m_{\tilde{g}}, m_{\tilde{t}} \leq 1000 \text{ GeV}$ ,  $\text{sign}(\mu) = -1, 1$ ,  $90 \text{ GeV} \leq m_A \leq 1000 \text{ GeV}$ ,  $-3 \leq A \leq 3$ . We impose the experimental constraints: accelerators data on supersymmetric and Higgs boson searches, measurements of the  $b \rightarrow s + \gamma$  decay and of the muon anomalous magnetic moment  $a_\mu \equiv (g_\mu - 2)/2$  (the range  $-160 \leq \Delta a_\mu \cdot 10^{11} \leq 680$  is used here for the deviation of the current experimental world average from the theoretical evaluation within the Standard Model). We notice that to satisfy the  $b \rightarrow s + \gamma$  constraint is not trivial at small  $m_A$  values, since it requires some cancellation between the contributions due to the Higgs-quark and the chargino-squark loops. However, it turns out that the extent of compensation between the two terms is limited to an effect of 30-60 %. The range used here for the branching ratio is  $2.18 \times 10^{-4} \leq BR(b \rightarrow s + \gamma) \leq 4.28 \times 10^{-4}$ . For  $(\Omega_{CDM} h^2)_{\min}$  we use here the value  $(\Omega_{CDM} h^2)_{\min} = 0.095$  [2], derived at the  $2\sigma$  C.L. from the analysis of Ref. [3].

As discussed in Refs. [1-2], neutralino configurations at small  $m_\chi$  have a dominant bino component with a small mixture with  $\tilde{H}_1^0$ , *i.e.* writing the neutralino as  $\chi \equiv a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$ , one has  $|a_1| \gg |a_3| \gg |a_2|, |a_4|$ . In this regime the ratio  $|a_3|/|a_1|$  is

given by the analytic expression

$$\frac{|a_3|}{|a_1|} \simeq \sin \theta_W \sin \beta \frac{m_Z}{|\mu|} \lesssim 0.42 \sin \beta, \quad (1)$$

where in the last step we have taken into account the experimental lower bound  $\mu \gtrsim 100 \text{ GeV}$ . The allowed range of the ratio  $|a_3|/|a_1|$  for increasing values of  $m_\chi$  is displayed in Fig. 1. The upper boundary line is given by intrinsic properties in the diagonalization of the neutralino mass matrix and is obtained by maximizing the parameters  $M_2$  and  $\tan \beta$  and by minimizing  $\mu$  (for very small  $m_\chi$ , Eq. (1) applies). The lower boundary line is derived from the condition  $\Omega_\chi \leq (\Omega_{CDM})_{\max}$  (using Eq. (5) of Ref. [2]). These two boundary lines fit well with the scatter plot obtained by a numerical scanning of the supersymmetric parameter space, also displayed in Fig. 1. For  $m_\chi \gtrsim 20 \text{ GeV}$  the cosmological bound is satisfied by the  $\tilde{\tau}$ -exchange in the annihilation cross-section, and  $|a_3|$  is no longer constrained from below. The lower bound on  $|a_3|/|a_1|$  in the scatter plot of Fig. 1 is due to the upper value (1 TeV) in the range of  $\mu$  employed in our calculation.

In Fig. 2 we show a scatter plot of the quantity  $\xi \sigma_{\text{scalar}}^{(\text{nucleon})}$  as a function of  $m_\chi$ . This scatter plot shows that, in the mass range  $6 \text{ GeV} \lesssim m_\chi \lesssim 25 \text{ GeV}$ , the quantity  $\xi \sigma_{\text{scalar}}^{(\text{nucleon})}$  falls in a narrow funnel (see property (2) above); this funnel is delimited from below by configurations with  $\Omega_\chi h^2 \sim (\Omega_{CDM} h^2)_{\max} = 0.131$ , and delimited from above by supersymmetric configurations with a very light Higgs boson (close to its lower experimental bound of 90 GeV) and with an  $\Omega_\chi h^2$  below  $(\Omega_{CDM} h^2)_{\min}$ . For  $m_\chi \lesssim 10 \text{ GeV}$  only values of  $30 \lesssim \tan \beta \leq 50$  and  $100 \text{ GeV} \leq |\mu| \lesssim 300 \text{ GeV}$  contribute, while in the interval  $10 \text{ GeV} \lesssim m_\chi \lesssim 25 \text{ GeV}$   $\tan \beta$  extends also to lower values around 8 and  $|\mu|$  is not significantly constrained. Moreover, for  $m_\chi \lesssim 20 \text{ GeV}$ ,  $m_A$  is strongly bounded from above by  $(\Omega_{CDM} h^2)_{\max}$ , as shown in Fig. 3 of Ref. [2]. Notice that the dip at  $\simeq 45 \text{ GeV}$  is due to the Z-pole in the annihilation cross-section.

It is also remarkable that, within the funnel, the size of  $\xi \sigma_{\text{scalar}}^{(\text{nucleon})}$  is large enough to make light relic neutralinos explorable by WIMP direct experiments with the current sensitivities. To illustrate this point, let us turn now to a comparison of our predictions with experimental data [5, 6] which became available after our analysis of Refs. [1, 2] and with those of Ref. [7].

In Refs. [1, 2] we anticipated that a detector with a high exposure and a low threshold such as DAMA [8] might provide significant information, not only for neutralinos with  $m_\chi > 50 \text{ GeV}$ , but also for neutralinos in the mass range  $6 \text{ GeV} \lesssim m_\chi \lesssim 50 \text{ GeV}$ . In Ref. [2] we could only give an estimate of the expected effects in the measurement of the annual-modulation variation

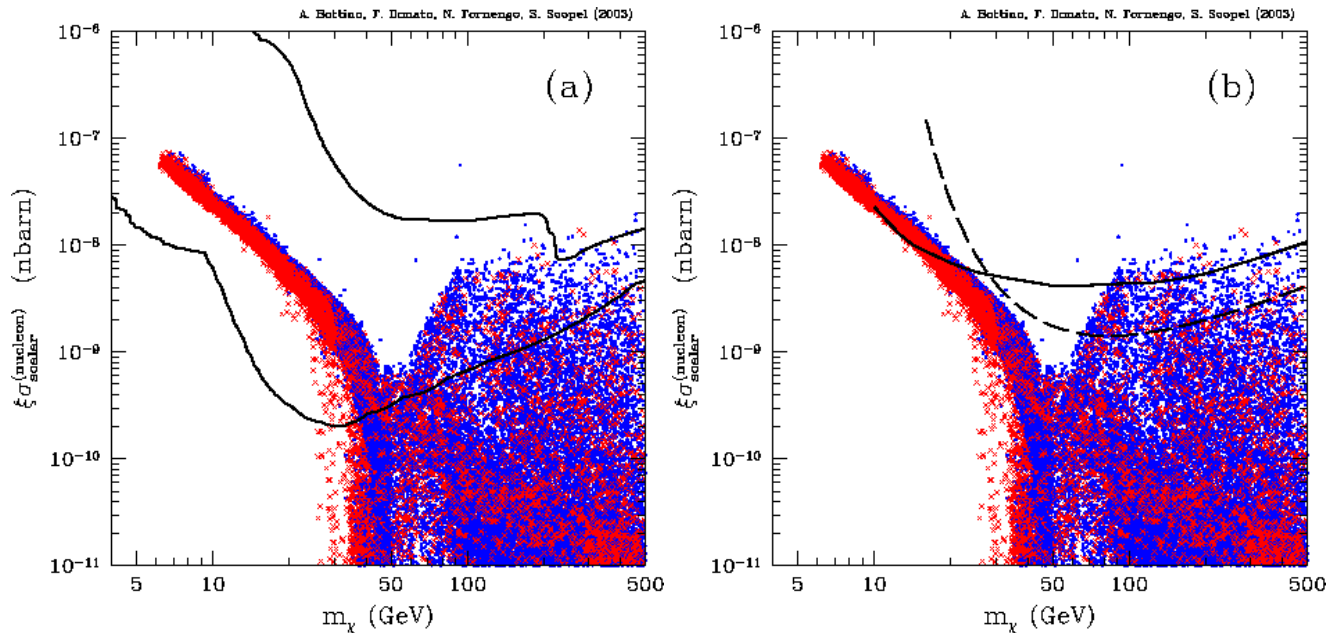


FIG. 2: Scatter plot of  $\xi\sigma_{\text{scalar}}^{(\text{nucleon})}$  versus  $m_\chi$ . Crosses (red) and dots (blue) denote neutralino configurations with  $\Omega_\chi h^2 \geq (\Omega_{\text{CDM}} h^2)_{\text{min}}$  and  $\Omega_\chi h^2 < (\Omega_{\text{CDM}} h^2)_{\text{min}}$ , respectively ( $(\Omega_{\text{CDM}} h^2)_{\text{min}} = 0.095$ ) (a) The curves delimit the DAMA region where the likelihood-function values are distant more than  $4\sigma$  from the null (absence of modulation) hypothesis [5]; this region is the union of the regions obtained by varying the WIMP DF over the set considered in Ref. [9]. (b) The solid and the dashed lines are the experimental upper bounds given by the CDMS [6] and the EDELWEISS [7] Collaborations, respectively, under the hypothesis that the WIMP DF is given by an isothermal distribution with a standard set of astrophysical parameters.

performed by the DAMA Collaboration, since no analysis of the experimental data at low WIMP masses was available at that time.

Now, the recent presentation of new results by the DAMA Collaboration [5] allows us to compare directly our theoretical predictions to actual experimental data. In fact, one has now the results of a much larger exposure than in the past, about  $108,000 \text{ kg} \cdot \text{day}$  and, most important, an analysis of the full set of experimental data in terms of a spin-independent effect over an unconstrained range for the mass of a generic WIMP. The results of this analysis are reported in Fig. 2(a), where the contour line (after Fig.28 of Ref. [5]) delimits a region of the  $m_\chi - \xi\sigma_{\text{scalar}}^{(\text{nucleon})}$  plane, where the likelihood-function values are distant more than  $4\sigma$  from the null (absence of modulation) hypothesis. In deriving this contour line, the DAMA Collaboration has taken into account a rather large class of possible phase-space distribution functions (DF) for WIMPs in the galactic halo. The categories of DFs considered in Ref. [5] are those analyzed in Ref. [9]; the annual-modulation region displayed in Fig. 2(a) is the union of the regions obtained by varying over the set of the DFs considered in Ref. [9]. From Fig. 2(a) we derive that the entire population of relic neutralinos with  $m_\chi \lesssim 25 \text{ GeV}$  as well as a significant portion of those with a mass up to about  $50 \text{ GeV}$  are within the

annual-modulation region of the DAMA Collaboration. Thus, this yearly effect could be due to relic neutralinos of light masses, in alternative to the other possibility which we already discussed in Refs. [4] on neutralinos with masses above  $50 \text{ GeV}$ , and which is reconfirmed by the present analysis.

Another experiment of WIMP direct detection, run by the CDMS Collaboration, has recently published new data [6]. Their results are given in terms of an upper bound <sup>1</sup> on  $\sigma_{\text{scalar}}^{(\text{nucleon})}$  for a given DF (an isothermal distribution) and for a single set of the astrophysical parameters:  $\rho_0 = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$ ,  $v_0 = 220 \text{ km} \cdot \text{s}^{-1}$  ( $v_0$  is the local rotational velocity). This upper bound is displayed in Fig. 2(b) together with our theoretical scatter plot. Thus, we see that *in case of an isothermal DF with the representative values of parameters given above*, a sizeable subset of supersymmetric configurations in the mass range  $10 \text{ GeV} \lesssim m_\chi \lesssim 20 \text{ GeV}$  would be incompatible with the experimental upper bound (together with some

<sup>1</sup> We consider here only the upper bound derived by the CDMS Collaboration without neutron subtraction. The upper limit obtained by subtracting an estimated neutron background appears too model-dependent; this point will be overcome, when the CDMS experiment is run in an underground location, as foreseen by the Collaboration.

configurations with  $m_\chi \gtrsim 80$  GeV). However, this conclusion cannot be drawn in general. In fact, to set a solid constraint on the theoretical predictions, it is necessary to derive from the experimental data the upper bounds on  $\xi\sigma_{\text{scalar}}^{(\text{nucleon})}$  for a large variety of DFs and of the corresponding astrophysical parameters (with their own uncertainties); the intersection of these bounds would provide an absolute limit to be used to possibly exclude a subset of supersymmetric population. An investigation by the CDMS Collaboration along these lines would be very interesting.

Among other experiments of WIMP direct detection, the EDELWEISS experiment has published an upper bound which somewhat approaches the region of the low-mass neutralino population. This upper limit, again provided for a single DF (the isothermal sphere with a standard set of astrophysical parameters) is also displayed in Fig. 2(b); it turns out to be marginal for the low-mass population, since it is tangent to our supersymmetric scatter plot (at  $m_\chi \sim 30$  GeV). The argument given before applies again in this case; one should vary the analytical forms of the DF, in order to derive a model-independent bound on  $\xi\sigma_{\text{scalar}}^{(\text{nucleon})}$ . As for the low-mass configurations ( $m_\chi \lesssim 50$  GeV), since the current upper limit is already marginal for the isothermal DF, one does not expect any model-independent constraint. However, useful constraints could be derived for higher masses.

In conclusion, we have shown that the experimental exploration of the low-mass neutralino population, theoretically analyzed in our papers of Refs. [1, 2], is already under way in case of some experiments of WIMP direct detection and within the reach of further investigation in the near future.

We have compared our predictions with available results of various experiments separately, since the experimental results of different Collaborations are not all derived under the same assumptions on the WIMP phase-space distribution function. A more effective comparison of theoretical results with experimental data will be feasible, only when the analysis of different experimental results in terms of  $m_\chi - \xi\sigma_{\text{scalar}}^{(\text{nucleon})}$  is presented for

each analytic form of the DF, separately. This is also the unique way of comparing results of different experiments among themselves.

We finally notice that, in direct detection experiments, lighter WIMPs have to be faster, as compared to the heavier ones, in order to deposit a recoil energy above the energy threshold. As a consequence, for light WIMPs the calculation of expected rates and the determination of upper limits on the cross-section are very sensitive to the value assigned to the escape velocity and, more generally, to the details of the high-velocity tail of the DF. This introduces an important uncertainty, since for high-velocity WIMPs the assumption of thermalization, which for instance is assumed in all the models considered in the analysis of Ref. [9], is less robust than for the bulk of the distribution: non-thermal components, such as streams, could have a sizeable or even dominant weight, affecting the usual estimates for expected rates.

#### NOTE ADDED.

After submission of the present paper, updated evaluations of the  $e^+ - e^-$ -based and  $\tau$ -based lowest-order (LO) hadronic polarization contribution to the muon magnetic moment have been presented by M. Davier et al. (hep-ph/0308213). In order to obtain a conservative range for the deviation of the standard model value of  $a_\mu$  from its experimental determination, we consider the  $e^+ - e^-$ -based LO hadronic contribution by K. Hagiwara et al. (hep-ph/0209187) together with the  $\tau$ -based LO hadronic contribution by M. Davier et al. Combining the evaluation by K. Hagiwara et al. with the other standard model contributions, we find for the deviation from the world average experimental result the  $2\sigma$  range:  $133 \leq \Delta a_\mu \leq 569$ . Instead, using the  $\tau$ -based Davier et al. result, one obtains the  $2\sigma$  interval:  $-142 \leq \Delta a_\mu \leq 286$ . If we combine conservatively these two determinations we finally have  $-142 \leq \Delta a_\mu \leq 569$ . Employing this range instead of the one used in the derivation of the scatter plot in Fig. 2 does not modify the features of the plot in any significant way.

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